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Assessing nutrient fluxes in a Vietnamese rural area despite limited and highly uncertain data

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ABSTRACT

Material flow analysis (MFA) is a useful methodology to describe and quantify complex systems based on the law of mass conservation. It was further adapted to suit the specific conditions in developing countries where the available data is scarce and uncertain. The 'adapted MFA' methodology optimises the number of parameters, describes these parameters as probability distributions and assesses the accuracy and uncertainty of the model values by Monte Carlo simulation.

This study illustrates the first successful application of the 'adapted MFA' methodology in a small and low-income area including two neighbouring communes in rural northern Vietnam, where environmental sanitation and traditional agricultural practices are strongly interlinked and have an impact on the surrounding environment. Moreover, data on this area is typically scarce and uncertain. The obtained results reveal that the agricultural system was a significant source of nutrients (nitrogen (N) and phosphorous (P)), which affect the surrounding environment mainly due to the overuse of chemical fertilizers. Every year, there were 103 ± 39 tonnes of N released into the atmosphere, 25 ± 3 tonnes of N leached to the surface water and 14 ± 2 tonnes of P accumulated in the soil, all originating from the applied chemical fertilizers. In addition, the sanitation system was also a critical source of nutrients that enter the surface water. 69 ± 6 tonnes of N and 23 ± 4 tonnes of P came from households through effluents of on-site sanitation systems (such as latrines and septic tanks) and were directly discharged to surface water every year. Moreover, the whole system annually generated a large nutrient source (214 ± 56 tonnes of N; 58 ± 16 tonnes of P) in the form of wastewater, faecal sludge, animal manure and organic solid wastes.

The validated MFA was used to model different scenarios for the study site. The first scenario demonstrated that if nutrient management is not improved, wastewater as well as faecal sludge and organic solid waste are expected to double in the year 2020 as compared to that in 2008. The second and third scenario revealed possible strategies to significantly reduce environmental pollution and reuse nutrient sources predicted to be available in the year 2020.

1. Introduction

The material flow analysis (MFA) methodology was first applied to quantify industrial processes in the 1990s (Jelinski et al., 1992; Erkman, 1997). It has also been proved to be a suitable instrument for early recognition of environmental problems in developed countries by quantifying material flows in the system and then forecasting the impact of possible interventions on the environment (Brunner and Baccini, 1992; Drolc and Konan, 1996; Zessner et al., 1998; Zessner and Kroiss, 1999; Zessner and Gils, 2002). In recent years, this methodology has been modified to consider the uncertainty in input data sources (Binder et al., 2004). As a result, the modified MFA method has also been successfully applied in developing countries that typically face considerable data scarcity and uncertainty problems.

The Pak Kret municipality, Nonthaburi province, Thailand applied MFA in order to assess mitigating measures to maximize nutrient recovery and minimize environmental pollution (Sinsupan et al., 2005). Results revealed that creating a wastewater treatment plant and composting solid wastes could reduce nitrogen loading to the environment by 45% and optimize nutrient recovery.

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Therefore, MFA might be effectively applied during environmental sanitation planning in developing countries.

The city of Kumasi, Ghana was another example of MFA application (Belevi et al., 2000). The data obtained revealed that private households were a key contributor to the organic material fluxes of nitrogen (N) and phosphorus (P). MFA results confirmed that measures taken at the household level such as appropriate household waste management greatly enhanced resource recovery and environmental protection in Kumasi.

Furthermore, MFA was also useful in quantifying N and P flows in urban areas of Hai Phong city, Vietnam, including five urban districts. The aim was to identify weaknesses related to nutrient management in this region (Thuy and Aramaki, 2010). MFA results demonstrated that appropriate management of human excreta and wastewater from households was needed to mitigate the environmental impacts of these nutrients.

In particular, this MFA methodology was profitably adapted once more by introducing innovative methods to fill data gaps and reduce data inaccuracy. The first test of this 'adapted MFA' was in Hanoi, the capital of Vietnam, studying the environmental sanitation system in terms of N and P (Montangero and Belevi, 2008). Initially, the sensitivity analysis methodology identified parameters that had the biggest impact on model outcomes, which were then needed to be reassessed more accurately using the expert judgment method (Montangero and Belevi, 2007; Montangero et al., 2007). The number of primary data required was reduced by using approximate values first (secondary data and assumptions). In addition, MFA was coupled with quantitative microbial risk assessment and stakeholder analysis to implement the Household-Centred Environmental Sanitation approach, and was used to assess an existing environmental sanitation system and evaluate potential future systems with regard to resource management, water pollution control and microbial health risks. These methods could also be used to identify and involve stakeholders in order to plan demand-responsive environmental sanitation systems. Relationships between the various tools and between the planning approach and the tools were discussed as a basis for their integration (Montangero et al., 2010).

The above 'adapted MFA' was also successfully applied in a multi-provincial area like Thachin River Basin, Thailand, including six provinces and a part of Bangkok. This study provided an overview of the origins and flow paths of the various point- and non-point pollution sources of the entire area in terms of N and P (Schaffner et al., 2009a, 2009b, 2010). The results showed that aquaculture (as a point source) and rice farming (as a non-point source) were the key nutrient (N and P) sources in this river basin. When simulated and measured nutrient concentrations were compared, retention in the river system appeared to be significant.

While the 'adapted MFA' methodology has been successfully applied in the urban context of Vietnam, its applicability in the rural context has not yet been demonstrated. In addition, environmental sanitation coverage in rural areas of Vietnam is far lower than in cities, resulting in an alarming increase in the level of environmental pollution (MONRE, 2006). The uniqueness of Vietnam rural areas is the close link between environmental sanitation systems and agricultural activities including rice production, husbandry and fish farming. Though the number of rural households with sanitary latrines increased from 52% in 2004 to 67% in 2010, there is still 8% open defecation (UNICEF, 2010). In addition, because of the in situ recycling processes, manure waste from pigs, cows and buffaloes has not been estimated thus far. Runoff from paddy fields or vegetable and fruit gardens carries with it a great amount of chemical fertilizer rich in ammonium, nitrate and phosphate, causing the eutrophication of lakes and ponds (Cau, 2007). This kind of runoff is one of the major pollution sources of the Nhue River (ADB, 2007). From a reuse perspective, it would be interesting to reclaim nutrients from the above sources for agricultural activities. This would not only reduce river pollution but also improve the cost–benefit ratio for poor farmers.

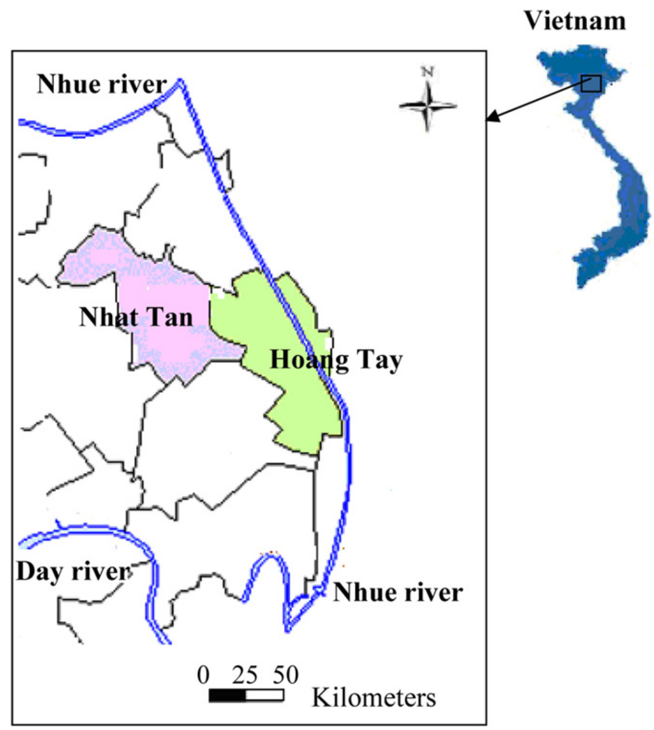

Fig. 1. Study site – Hoang Tay and Nhat Tan communes in Hanam province, Vietnam.

As can be seen, MFA methodology could serve as a profitable assessment and planning tool for nutrient resource management. This paper is the first investigation of 'adapted MFA' applicability in a typical rural context of Hoang Tay and Nhat Tan communes, Hanam Province, Vietnam where data sources are scarce and highly inaccurate though environmental and health risk status is alarming. This research focuses on assessing the suitability of the methodology for illustrating interconnections between the environmental sanitation system and the agricultural system, their impact on the surrounding environment in terms of nutrients N and P and identifying relevant nutrient sources. The current study is part of a large research project designed to assess the environmental and health risks related to wastewater and excreta reuse in the Hanam province in northern Vietnam (Nguyen-Viet et al., 2009).

2. Methodology

2.1. Description of study area

The target site, covering around 8 km^2, includes two neighbouring communes of Hoang Tay and Nhat Tan in the Hanam province, and is located about 60 km south of Hanoi, northern Vietnam (Fig. 1). In the year 2008, the population of this site was 16,178, among a total of 4047 households (Hoang Tay and Nhat Tan offices, 2000–2008). These two low-income communes represent typical land use pattern in northern Vietnam, where residents' houses and water sources are very close to barns and within a limited space. Residential areas are surrounded by aquaculture and agriculture. Households mostly rely on very rudimentary forms of on-site sanitation facilities, for instance, pit latrines, pour-flush latrines and septic tanks. In addition, human and animal faeces are used as fertilizer for paddy fields, and in some cases, are directly dumped into ponds to feed fish. Greywater is released without treatment into drainage networks, and is then passed into canals or the Nhue River together with the onsite sanitation system effluent. It is important to note that the Nhue River is one of the three most polluted rivers in Vietnam because it receives wastewater from domestic activities, industries and hospitals in high density urban areas such as the Hanoi Capital (MONRE, 2006). However, the Nhue River is still the main water source for irrigation and fish ponds. As for solid waste, it is not totally uncontrolled but it is poorly controlled.

2.2. Methodology

Based on the 'adapted MFA' framework (Montangero, 2006), a research flowchart for this study was simplified and represented in three main steps, as shown in Fig. 2.

2.2.1. Model development

(a) MFA system development

Based on the literature review, information available on the internet, published reports and previous researches, the MFA system used in this study generally describes all local human activities and surrounding environments as processes and describes interlinks among these in terms of indicator (N and P) flows in 2008.

(b) MFA equation development

There are two types of equations in a MFA model (Brunner and Rechberer, 2003). One is the balance equation formulated for each process within the system border on the basis of the law of mass conservation.

$$\frac{dM_i^j}{dt} = \sum_r A_{i,r-j} - \sum_s A_{i,j-s} \quad (1)$$

where dM_i^j/dt: stock change rate of substance i within process j through time t; $\sum_s A_{i,j-s}$: total of substance i from different processes r entering process j; $\sum_r A_{i,r-j}$: total of substance i leaving process j through different processes s.

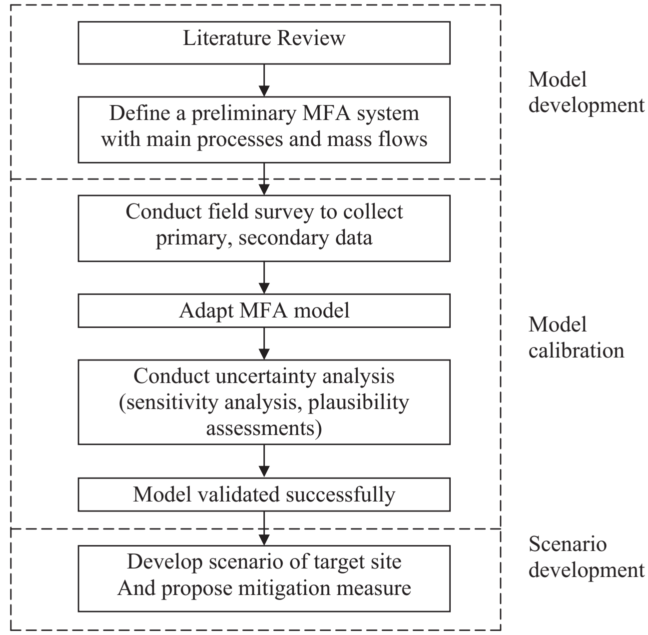

Fig. 2. Simplified MFA framework (adapted from Montangero, 2006).

The second is the model equation, which was developed using information from the literature review and short interviews with experts.

$$\sum_r A_{i,r-j} = f(p_1, p_2, \ldots, p_n) \quad (2)$$

where $p_1, p_2, \ldots, p_n$: parameters represent the variables in the system. These parameters were described as probability distributions and could be replaced by other parameters that are easily estimated or measured (see list of parameters and MFA equations shown in Table 1).

Table 1
List of necessary data (Hoang Tay and Nhat Tan offices, 2000–2008; Montangero, 2006) and detailed equations in Household (1) process of MFA calibration.

Symbol	Description of data	Unit	Statistical distribution	Mean ± standard deviation
n	Number of inhabitants in target site	Inhabitants	Normal	16,293 ± 1600
rgrey_ST	Ratio greywater to septic tank	%	Lognormal	0.1 ± 0.10
rgrey_AC	Ratio greywater to aquaculture	%	Lognormal	0.5 ± 0.10
aHH_RW	Household rainwater consumption	l/cap × day	Normal	50 ± 10.00
aHH_GW	Household groundwater consumption	l/cap × day	Normal	70 ± 10.00
CN,RW	N content rainwater	mg/l	Lognormal	2.5 ± 0.50
CN,GW	N content groundwater	mg/l	Lognormal	6.3 ± 0.80
aN,kitc_wastes	N load in kitchen waste	gN/cap × day	Lognormal	0.8 ± 0.20
aN,food	N load food	g/cap × day	Normal	6.5 ± 0.70
aN_excreta	N load excreta	gN/cap × day	Normal	6.1 ± 0.60
aN_grey	N load greywater	gN/cap × day	Normal	0.4 ± 0.05
rN_body_loss	N losses from human body to the air	–	Lognormal	0.04 ± 0.01

	Description of flow (tonnes N/year)	Equation
$dM_N^{(1)}/dt$	Amount of N storage in the system every year (stock change rate of household process)	(AN6–1 + AN16–1 + AN17–1) – (AN1–2 + AN1–3 + AN1–4 + AN1–13 + AN1–17)
AN6–1	N flow from market process to household process	$n \times$ aN,food $\times 365 \times 10^{-6}$
AN16–1	N flow from soil/groundwater process to household process	$n \times$ aHH_GW × CN,GW $\times 365 \times 10^{-9}$
AN17–1	N flow from atmosphere process to household process	$n \times$ aHH_RW × CN,RW $\times 365 \times 10^{-9}$
AN1–2	N flow from household process to on-site sanitation process	$n \times$ (aN_excreta $\times 10^{-6}$ + aN_grey × rgrey_ST $\times 10^{-9}$) × 365
AN1–3	N flow from household process to drainage system process	$n \times$ aN_grey × (1 – rgrey_ST – rgrey_AC) $\times 365 \times 10^{-9}$
AN1–4	N flow from household process to "solid wastes collection" process	$n \times$ aN,kitc_wastes $\times 365 \times 10^{-6}$
AN1–13	N flow from household process to aquaculture process	$n \times$ aN_grey × rgrey_AC $\times 365 \times 10^{-9}$
AN1–17	N flow from household process to atmosphere process	rN_body_loss × AN6–1

2.2.2. Model calibration

The MFA model was adapted on the basis of both primary and secondary data. Primary data included field observations, questionnaire surveys for local households, interviews with key informants and experts in local, provincial and national governmental agencies, and secondary data included statistics and reports from local offices collected during the field survey. This MFA model was calibrated consequently. Both collected data and estimated results from the model were used in subsequent uncertainty analyses, sensitivity analysis and plausibility assessment.

(a) Sensitivity analysis

Sensitivity analysis was performed to quantify the effect of a 10% increase in each parameter on the simulation result according to the Hanoi case study (Montangero and Belevi, 2007; Montangero et al., 2007). This quantification identified the parameters that had a more significant influence than the others. The list of sensitive parameters was then taken into account when, if necessary, conducting further field surveys in designing effective scenarios.

(b) Plausibility assessment

Plausibility assessment was conducted to evaluate the accuracy of simulated MFA results using a list of plausibility criteria that were successfully utilized in many previous studies (Nga et al., 2011). One thousand iterations were set to run Monte Carlo simulation using Visual Basic for Applications (VBA, Microsoft Excel, Microsoft Office®). A criterion would pass the assessment if at least 68% of the above generated values were in the corresponding plausibility range (Montangero and Belevi, 2007). Moreover, for those plausibility criteria that did not pass, the respective sensitive parameters were reassessed by carrying out additional literature reviews or surveys. These steps were repeated until all plausibility criteria passed (Montangero and Belevi, 2007; Montangero et al., 2007).

2.2.3. Scenario development

The validated MFA model was used to develop different scenarios for the target site. Since the development strategy for this area was under consideration, Scenario 1 was designed to visualize the local environment in the year 2020. The status of year 2020 was regressed on the basis of the previous nine years of statistical data (2000–2008) (Hoang Tay and Nhat Tan offices, 2000–2008), i.e. population increase would be 1.16% per year; the number of pigs, cattle and poultry would triple and agriculture farming area and sanitation systems would remain the same as in 2008. Scenario 2 was created as a mitigation measure for 2020, reducing the quantity and improving the quality of wastewater from onsite sanitation systems discharging to drainage systems in these two poor communes. This scenario was based on the recommendation of environmental sanitation experts during the field survey, which included replacing pit latrines and pour-flush latrines with septic tanks; pre-treating greywater using septic tanks and maintaining the same number of biogas latrines as in 2008. Scenario 3 was also developed as a solution for 2020, which included reusing huge available nutrient sources in drainage water instead of purchasing chemical fertilizers. Accordingly, an assumption of scenario 3 was reduction of the total chemical fertilizers used in 2008 by half, and then directly connecting drainage to paddy fields to reuse the drainage water in the paddy fields.

3. Results and discussion

3.1. Model development

There were twelve processes, divided into three focus groups: the environmental sanitation system (household, on-site sanitation system, drainage system, solid waste collection, landfill processes), agricultural activities (paddy field, aquaculture, livestock production) and the surrounding environment (Air, Surface water, Soil/groundwater). Moreover, the process 'Market' was also included in the MFA, acting as a 'platform' for the exchange of goods produced in the target area and distributed to the households in and outside communes, and where imported products such as food and agricultural input (fertilizers) were distributed to the households and agricultural processes (Montangero et al., 2007). Regarding target indicators N and P, interlinks among these processes were created as shown in Fig. 3a and b.

3.2. Model calibration

Table 1 provides the detailed data collected and model equations used for calibrating the Household (1) process, for instance. After all processes are calibrated, MFA calibration results are shown in Fig. 3—the environmental status of the target site in 2008. Boxes and arrows represent processes and nutrient flows, respectively. The wider arrows represent the larger nutrient flows among processes. The black arrows indicate very small nutrient flows compared with the others. The number in each process box indicates the amount of nutrients stocked in that process.

Close interconnections between agricultural activities and the environmental sanitation system and their critical impact on the surrounding environment as well as on nutrient sources were quantified and visualized at this stage. As can be seen in Fig. 3, nutrient sources of surface water (the Nhue River) were water runoff from the paddy field process and drainage system, including greywater from the household process, wastewater after washing pig farms of the livestock process and blackwater from the on-site sanitation system process. Moreover, the nutrient load on the atmosphere was estimated on the basis of nitrogen emissions from applied chemical fertilizers, commercial feed for fish or animal manure and urine coming from paddy field, aquaculture, livestock and on-site sanitation system processes, respectively. Nutrient sources to the Soil/groundwater environment included leachate from chemical fertilizers used in paddy fields or water from aquaculture, drainage, on-site sanitation systems (pit latrines, pour-flush latrines and septic tanks) or landfills and uncollected cattle manure.

Fig. 3 illustrates the fact that the market process was the source as well as the destination of almost all large arrows in the system. The market process was considered to be the platform for nutrient supply of the target site as well as a nutrient exchange to other sites even outside the system. The main annual nutrient sources of the system through Market processes were chemical fertilizers for paddies and commercial food supplied for fish and animals (461 ± 76 tonnes of N and 109 ± 42 tonnes of P). In addition, products from aquaculture, livestock and paddy field process were nutrient sources which were distributed inside or exported outside the area annually (149 ± 52 tonnes of N and 24 ± 7 tonnes of P).

On the other hand, there were significant nutrient sources generated by the whole system every year (214 ± 56 tonnes of N and 58 ± 16 tonnes of P) in the form of wastewater, organic solid wastes or faecal sludge. Fifty-three percent of all N and 50% of all P came from pig manure (112 ± 23 tonnes of N and 42 ± 5 tonnes of P). In addition, Fig. 3 also indicates the significant connections between Livestock and Paddy field were supplying manure for

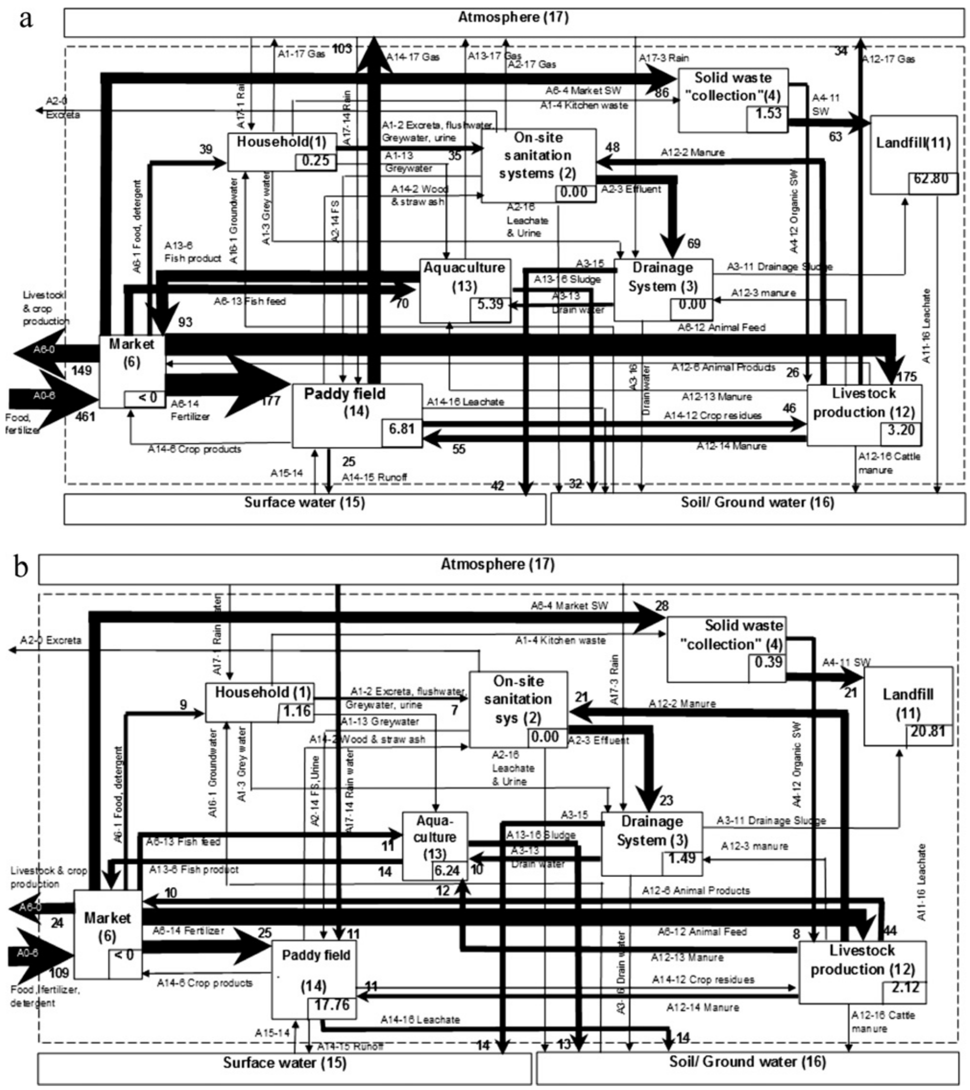

Fig. 3. MFA results in year 2008 for nitrogen (a) and phosphorous (b) (unit: tonnes/year). Boxes and arrows represent processes and nutrient flows, respectively. The wider arrows represent the bigger nutrient flows among processes. The small arrows indicate very little nutrient flows compared to the others. The number in each process box represents the amount of nutrients stocked in that process.

paddy fields (55 ± 12 tonnes of N, 11 ± 4 tonnes of P per year) and consuming residues (straw, vegetables, etc.) to feed pigs and poultries (46 ± 16 tonnes of N, 5 ± 1 of P per year). The pig manure (48 ± 6 tonnes of N and 21 ± 2 tonnes of P every year) represented 58% of all N and 75% of all P sources for the on-site sanitation system.

The impact of agricultural activities and the environmental sanitation system on the surrounding environment in terms of nutrients is also shown in Fig. 3.

Regarding the atmosphere, agricultural activities were the main emission source. Agriculture annually contributed 147 ± 54 tonnes of N, equal to 85% of all N emissions from the entire system, of which 64% was from applied chemical fertilizer and 21% was from animal manure. Nitrogen produced as a result of burning solid wastes in the solid wastes collections process or evaporation of water in the drainage system process were not included in the calculations.

Concerning the Nhue River surface water environment, the environmental sanitation system was the main nutrient source. The on-site sanitation system discharges 69 ± 6 tonnes of N and 23 ± 4 tonnes of P to the drainage system every year. This figure accounted for 93% of all N and 85% of all P in drainage water. In addition, 42 ± 7 tonnes of N and 14 ± 5 tonnes of P in drainage effluence reached the Nhue River each year. The other huge nutrient source of surface water was in runoff from paddy fields, which annually contributed 25 ± 3 tonnes of N originating from applied chemical fertilizer.

Finally, with regard to the soil/ground water environment, key factors were P accumulated in sludge from the Aquaculture system (32 ± 3 tonnes of N and 13 ± 2 tonnes of P) or P from applied chemical fertilizer accumulating in paddy fields (14 ± 2 tonnes of P) every year. For that reason, soil/ground water received 32 ± 3 tonnes of N and 27 ± 4 tonnes of P yearly from agriculture systems alone. Thus, the impact of agricultural activities and the environmental sanitation system on the atmosphere and surface water were far greater than on soil/ground water.

3.2.1. Sensitivity analysis

Because of the considerable impact of agricultural activities and the environmental sanitation system on surface water and the complexity of the procedure used to quantify nutrient flows, sensitivity analysis was applied in surface water and drainage system simulation processes. Table 2 presents a list of sensitive parameters which have a significant impact on the quantity of nutrients entering the drainage system and surface water.

As can be seen in Table 2, the amount of chemical fertilizer applied and the area of paddy fields had the largest effect on nutrient flows to the surface water. With an increase of 10% in each

Table 2
Effect of 10% parameter increase on nutrient flow to drainage system, surface water. Positive (+) or negative (−) in front of value represents increase or decrease, respectively, of total nutrients to the drainage system or surface water when increasing each parameter by 10% while keeping other parameters constant.

Parameter	% of total nutrient to *drainage system change*		% of total nutrient to *surface water change*	
	N	P	N	P
Population	+ 5.92	+ 4.12	+ 0.48	+ 0.50
Area of paddy fields	*na*[a]	*na*	+ 3.35	+ 7.10
Number of pigs	*na*	*na*	+ 1.31	+ 6.00
Amount of chemical fertilizer applied	*na*	*na*	+ 3.75	+ 8.95
Ratio of households equipped with				
Septic tank	+ 0.30	+ 2.13	+ 0.83	+ 3.25
Pour-flush latrine	+ 0.10	+ 0.98	+ 0.48	+ 3.20
Pit latrine	+ 0.09	+ 1.00	+ 0.78	+ 3.00
Biogas latrine	+ 6.85	+ 2.12	+ 1.25	+ 3.50
Faecal sludge emptying frequency factor for				
Septic tank	− 3.98	− 10.00	− 2.12	− 8.23
Pour-flush latrine	− 4.25	− 10.25	− 1.75	− 7.15
Pit latrine	− 7.00	− 10.00	− 4.30	− 7.00
Biogas latrine	− 8.00	− 11.49	− 5.98	− 9.14

[a] *na*: not available.

parameter, the total quantities of N (or P) entering the surface water grew by 3.75% (or 8.95%) and 3.35% (or 7.10%), respectively.

Furthermore, Table 2 indicates that the ratio of households equipped with different types of latrines was also a critical parameter. Among four types of on-site sanitation equipment, biogas latrines had the greatest impact on nutrient flows to surface water and drainage systems. If the number of biogas latrines increased by 10%, then the total amount of N or P released to the surface increased by 1.25% or 3.50%, respectively, and to the drainage system increased by 6.85% or 2.12%, respectively. On the other hand, the faecal sludge emptying frequency factor of latrines played an important role in reducing nutrient quantities to surface water and drainage systems. When the emptying frequency factor of biogas latrines increased by 10%, there was a decrease in total nutrients released into the drainage systems (8.00% of N and 11.49% of P) or the surface water (5.98% of N and 9.14% of P).

3.2.2. Plausibility assessment

Fig. 4 shows the plausibility assessment result from Criterion 1, which was created on the basis of the assumption that there was no N stock within the Household process (1). However, the N stock change rate ($dM_N^{(1)}/dt$) should be in a range $0 \pm 15\%$ of total N sources to this process (Montangero, 2006):

$$dM_N^{(1)}/dt = 0 \pm 15\% \quad \text{(Criterion 1)}$$

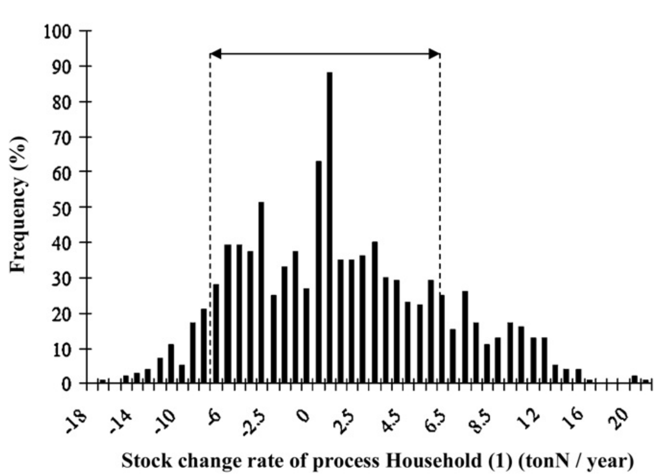

Fig. 4. Plausibility assessment results from Criterion 1. Model outcomes are illustrated as frequency histogram. Eighty-six percent of these generated values within the plausible range of stock change rate in Household (1) process.

Given the collected criterion, the N stock change rate of the Household process ($dM_N^{(1)}/dt$) was calculated on the basis of the law of mass conservation (Table 1). After running the Monte Carlo simulation, the obtained values of this stock change rate were demonstrated in Fig. 4. Values in the marked range represent values in the range 0 ± 6.45 tonnes of N (equals to 15% of total N input to Households). Therefore, 86% of obtained values were in range of Criterion 1. Hence, the MFA model passed this criterion. The other eleven criteria used to assess plausibility of MFA simulation outcome also passed. As a result, the MFA model was considered to be validated.

3.3. Scenario development

Fig. 5 shows the different scenarios for nutrient flows releasing to drainage systems, surface water or nutrient quantities in the sludge and solid waste for the simulated year (2020) compared with the current status of 2008.

Scenario 1 demonstrates that nutrient flows releasing to drainage systems or surface water, nutrients in sludge and organic solid waste would almost double in 2020. Furthermore, the total wastewater to drainage systems and surface water in 2020 was estimated to contain 374 ± 45 tonnes of N and 118 ± 15 tonnes of P. The amount of N was twofold and that of P was fivefold compared to amounts of applied chemical fertilizer for 2008. Therefore, in 2020, with the same paddy field area of 2008, this wastewater would contain enough nutrients to fertilize rich paddies without adding more chemical fertilizers. Moreover, other large nutrient sources from sludge and organic solid wastes (25 ± 4 tonnes of N and 14 ± 5 tonnes of P) should be considered as well.

Scenarios 2 and 3 are proposed solutions for the year 2020. Mitigation measures in scenario 2 would reduce the N and P discharged into drainage systems or surface water by nearly 50% and also decreased the N and P from sludge and organic solid waste by 32% and 43%, respectively. On the other hand, the load of N and P to drainage systems and surface water were still higher than the artificial fertilizer annually needed for paddy fertilisation. Therefore, even when the environmental sanitation system was improved as in scenario 2, nutrient sources would still be available for use in paddy fields. Based on assumptions in scenario 3, 50% of N and P in wastewater discharging to drainage systems would be reused as nutrient sources for paddy fields and chemical fertilizers applied would be reduced by half. Amount of nutrients releasing to surface water would accordingly decrease to 27% and 15% in terms of N and P, respectively.

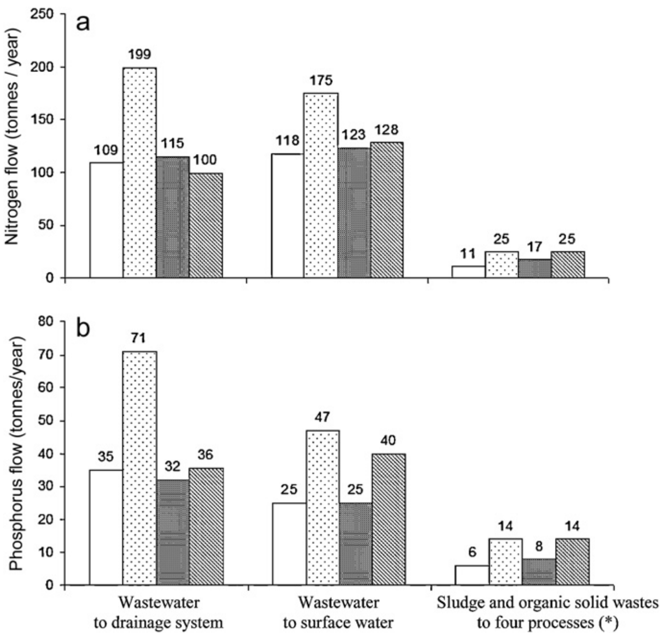

Fig. 5. Nitrogen (a) and phosphorous (b) flows in wastewater to the drainage system and to surface water and in sludge and organic solid waste to four processes. White bar represents status quo (year 2008); spotted bar represents forecasting situation of study site in year 2020 (Scenario 1); grey bar represents environmental sanitation solution for environmental status of year 2020 (Scenario 2); striped bar represents reduce and reuse solution for year 2020 (Scenario 3). Asterisk (*) indicates that four processes referred are onsite sanitation system, drainage system, solid waste collection and aquaculture.

4. Conclusions and recommendations

This research proves that the adapted MFA method is suitable to quantify nutrient flows in an area clearly faced with data uncertainty and scarcity. Because of the data specificity of developing countries, secondary data was used mainly as input data. By describing parameters as probability distributions instead of discrete data, the uncertainty of both parameters and outcome data could be assessed by its potential variation. Moreover, the developed mathematical model could be used to successfully quantify nutrient flows among environmental sanitation and agriculture systems and to assess the impact of these processes on the surrounding environment by conducting plausibility and sensitivity analyses.

This study is also the first fruitful investigation of 'adapted MFA' in a representative rural area in Vietnam. MFA simulation results pointed out critical control sources of nutrients in Hoang Tay and Nhat Tan communes, Hanam province, with overuse of chemical fertilizers in paddy fields, uncontrolled solid waste such as faecal and fish pond sludge, organic solid wastes and on-site sanitation system effluents. Consequently, options for nutrient resource management could be proposed, such as waste materials could be reused as fertilizers in agriculture and on-site sanitation technologies could be further developed and greatly improved. On the other hand, sustainable sanitation must consider the potential health impact of applying wastes, particularly human wastes. Untreated sewage sludge in manually worked rice paddies is potentially serious health hazard. Therefore, pre-treating organic solid wastes, like composting, should be done carefully at the household level.

In short, applying MFA as a part of environmental sanitation planning allows decision makers to identify potential problems and simulate the impact of remediation measures on resource consumption and environmental pollution in an integrated way. Suitable environmental sanitation options may thus be chosen by taking into account nutrient supply on the one hand and nutrient demand for food production on the other.

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